# FORECASTING THE MOTION OF TROPICAL CYCLONES USING A NUMERICALLY DERIVED STEERING CURRENT AND ITS BIAS [1,2]

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## ABSTRACT

The vector motion of severe tropical cyclones (including storm, hurricane/typhoon stages) is forecasted by a numerical scheme which involves two steps:

a. Numerical geostrophic steering of the center of the cyclone using the U.S. Navy Fleet Numerical Weather Facility's (FNWF) operationally produced smoothed isobaric height fields, called *SR*. The tropical perturbations are steered in 1-hr. time steps up to 72 hr., using winds derived from the *SR* analysis dated closest to warning time. *SR* 500 mb. in the Pacific and *SR* 700 mb. in the Atlantic gave the most accurate forecasts on tests of 10 northwest Pacific typhoons and all five north Atlantic tropical storms and hurricanes in the period Aug. 15–Nov. 1, 1965. Forecasts were made twice daily, 0600 and 1800 GMT, during this period using the best track information.

b. Next, the numerical-steering prediction is objectively modified to adjust for bias (i.e., deficiency in both zonal and meridional motion) by utilizing errors made in the most recent 12- and 24-hr. numerical-steering forecasts. Several modes of adjustment are employed; the most recent 12- (12- and 24-) hr. numerical-steering bias yields the most accurate correction of subsequent Atlantic (Pacific) forecasts out to periods of 72 hr. The optimal Naval Postgraduate School (NPGS) technique produces forecast errors ranging from an average of 4.2 kt. for 12-hr. forecasts to 6.2 kt. for 72-hr. forecasts. The U.S. Navy's official forecast accuracy is excelled by the NPGS scheme for all time periods.

Stratification of error statistics by area, trajectory, and stage of storm, intercomparison with ESSA's NHC-64 technique, discussion of merits and deficiencies of the research program relative to operational forecasts, and current experiments at FNWF are discussed.

## 1. INTRODUCTION

The Statement on Hurricanes issued by the American Meteorological Society [1] indicates that the desired degree of accuracy in forecasting the position of severe tropical cyclones is 50 mi. or less in a 24- to 36-hr. period. Such verification figures are far from being realized at the present time as noted in recently published error statistics from the U.S. Fleet Weather Facility, Jacksonville, Fla. [11], the U.S. Fleet Weather Central/Joint Typhoon Warning Center, Guam [9], the National Meteorological Center, ESSA, Washington, D.C. [12], and the National Hurricane Research Laboratory, ESSA, Miami, Fla. [5, 6, and 7].

The official hurricane/typhoon forecast, based on a careful consideration of all the available and pertinent subjective and objective techniques, is becoming increasingly dependent on the competitive contributions from the numerical approach. Both the U.S. Navy's and ESSA's numerical techniques already exceed the accuracy of many of the forecast schemes used faithfully by operational forecasters for many years [9, 11] and yet have potential for still greater improvement. Some of this potential has been realized recently by the development of a forecast scheme using certain numerically analyzed operational products generated by the U.S. Navy's Fleet Numerical Weather Facility (FNWF), Monterey, Calif. When coupled with an objective adjustment, dependent only on the characteristics of the storm's recent trajectory, the numerical scheme appears to offer a substantial increase in the accuracy of predicting movement of tropical cyclones, as compared to official forecasts, for forecast intervals up to 72 hr. The subject research reported on here represents a coordinated effort of the Naval Postgraduate School (NPGS) and FNWF, Monterey, Calif.

## 2. THE NUMERICAL-STEERING PROGRAM

In addition to the analyses of heights of mandatory isobaric levels, FNWF operationally produces analyses of certain additive components of these height fields on a twice-daily basis, 0000 GMT and 1200 GMT [4]. This unique numerical program, as developed for FNWF by Holl [3], performs a mathematical smoothing of the isobaric height fields with the degree of smoothing dependent on the amplitude and wavelength inherent in the isohyptic field. The arithmetic difference between the height field ($Z$) and the smoothed height field ($Z_{SR}$) is called the disturbance field ($Z_{SD}$). Thus, at any point on the isobaric surface $Z=Z_{SR}+Z_{SD}$. The $Z_{SR}$ pattern may be viewed as a space mean height field, portraying long wave features, while the $Z_{SD}$ contours depict the short or minor wave

[1] Limited version of this paper presented at the IUGG-AMS Fifth Technical Conference on Hurricanes and Tropical Meteorology, November 20-28, 1967, Caracas, Venezuela.

[2] Research supported by the Naval Weather Research Facility, Norfolk, Va., and Fleet Numerical Weather Facility, Monterey, Calif.

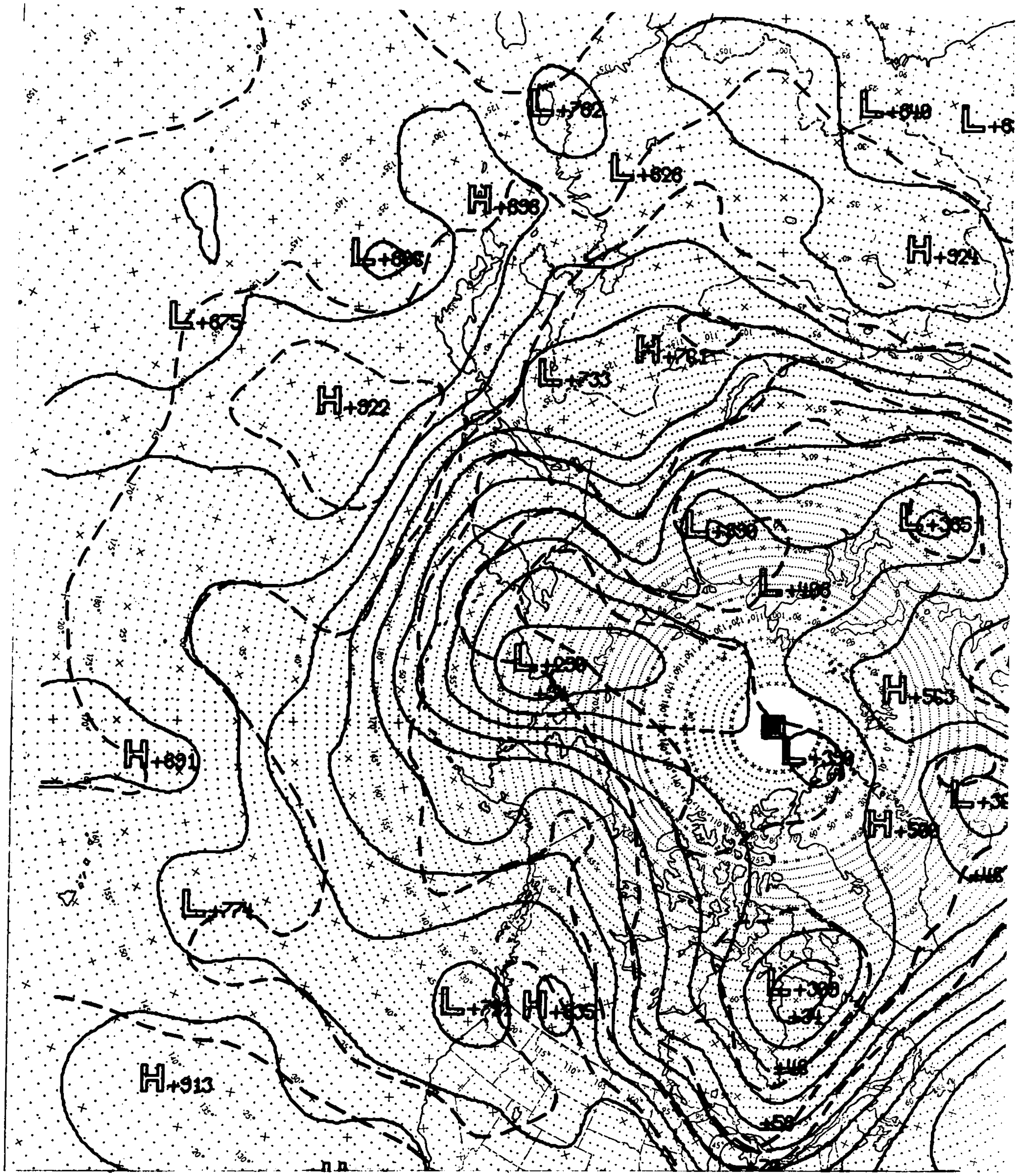



FIGURE 1.—Portion of FNWF's operational 500-mb. height ($Z$) and temperature analysis for 0000 GMT, Aug. 20, 1965. Contours at 60-m. interval (solid lines); isoline (center) labels in tens (units) of meters with thousands figure omitted. Isotherms (dashed lines) not labeled.

components of the original isohypses. Accordingly, the $Z_{SR}$ field, void of the disturbance flow to a certain degree, may be used to generate a current appropriate to the steering of tropical cyclones, which are regarded as the disturbance elements.

The foregoing interrelations between $Z$, $Z_{SR}$, and $Z_{SD}$ may be seen in figures 1, 2, and 3, each of which portrays a portion of these isobaric height fields for 0000 GMT, Aug. 20, 1965. The nature of the decomposition analyses in the case of severe tropical cyclones may be noted from

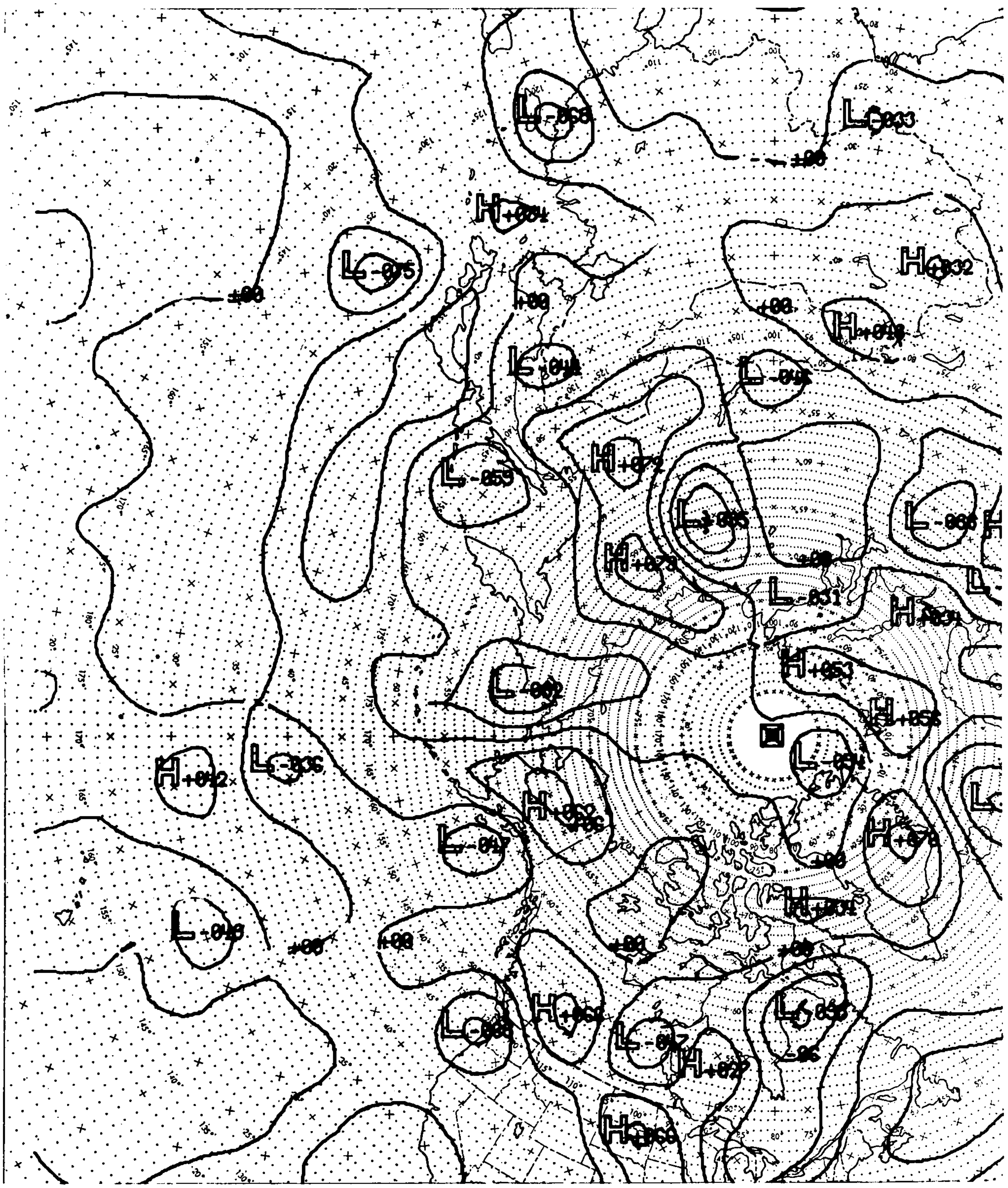


FIGURE 2.—Portion of FNWF's operational 500-mb. analysis of the disturbance component, $Z_{SD}$, derived from the 500-mb. height field, $Z$, at 0000 GMT, Aug. 20, 1965. Contours at 30-m. interval; isoline (center) labels in tens (units) of meters.

the situation just equatorward of Japan. Typhoon Lucy is located at 28.5°N., 140.2°E. at map time according to the best track position [8]. Figure 1 shows that FNWF's 500-mb. operational position of Lucy is very close to the best track location with a central 500-mb. height of 5806 m. The SD field (fig. 2) emphasizes the perturbation character of Lucy with a minimum value of −75 m. at the typhoon center. Thus, $Z-Z_{SD}=Z_{SR}$ or $5806-(-75)=5881$ m., which may be verified from figure 3.

Next, geostrophic *SR*-winds are computed to yield the steering or basic current used to forecast the motion of the tropical cyclone centers. Figure 4 is a schematic diagram

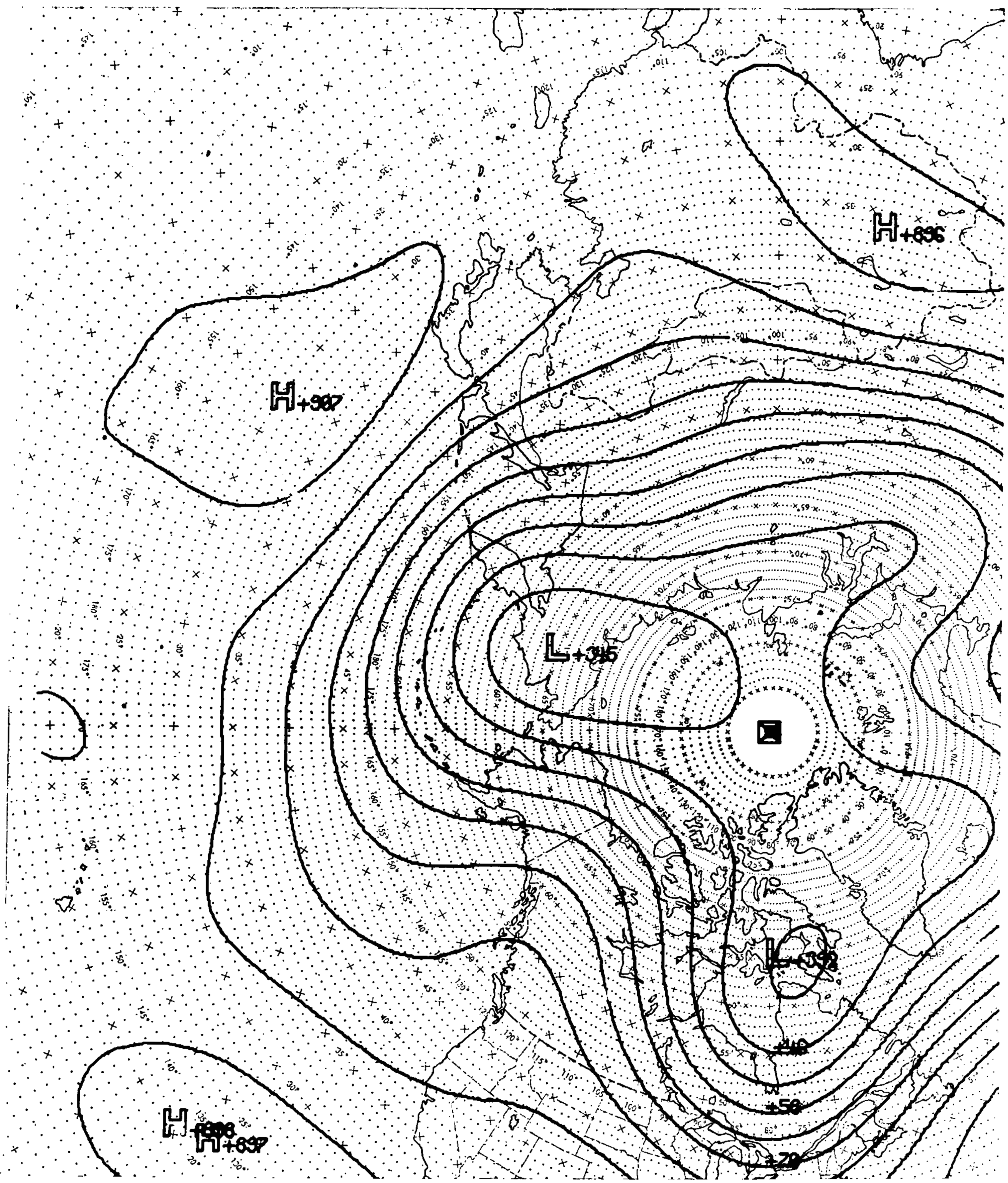



FIGURE 3.—Portion of FNWF's operational 500-mb. analysis of the residual or smoothed component, $Z_{SR}$, derived from the 500-mb. height field, $Z$, at 0000 GMT, Aug. 20, 1965. Contours at 60-m. interval; labels as in figure 1.

illustrating a section of the $Z_{SR}$ field appropriate to the Tropics with superimposed grid points representative of the FNWF linear $I, J$ mesh. The numerical computation of the geostrophic steering wind is accomplished by first locating the tropical cyclone center to the nearest 0.1° lat. and long. This point is identified as $I, J$ in figure 4. Next, geostrophic winds ($\mathbf{V}_g$) are computed by $I, J$ components and converted to latitude and longitude at each

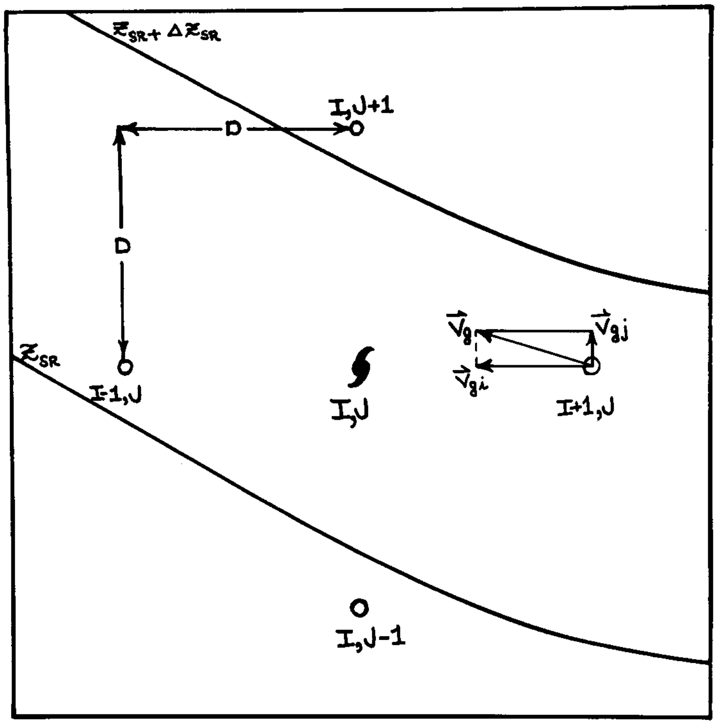



FIGURE 4.—Schematic representation of $Z_{SR}$ contours with superimposed FNWF linear grid. $I$, $J$ is tropical cyclone location. Geostrophic winds ($\mathbf{V}_g$) are computed, by component ($V_{gi}$, $V_{gj}$), at the four identified grid points, each at a distance $D$ from $I$, $J$.

of the four points, $I$, $J+1$; $I-1$, $J$; $I$, $J-1$; and $I+1$, $J$. An average of the four geostrophic winds is used to steer the cyclone center for 1 hr. For each subsequent hour, up to 72 hr., the process is repeated.

The finite difference form of the geostrophic wind equation necessitated obtaining height information from a distance of two mesh lengths from the cyclone center in the cardinal $I$, $J$ directions (i.e. at $I$, $J+2$; $I-2$, $J$; $I$, $J-2$; $I+2$, $J$). One mesh length, $D$ (as $I$, $J$ to $I+1$, $J$), is 381 km. at 60° lat., which reduces to about 305 km. at 30° lat., 275 km. at 20° lat., and 240 km. at 10° lat.

A potential problem with the Coriolis parameter, used in geostrophic wind computations at low latitudes, was avoided by using a modified form of the sine function for latitudes less than 30°:

$$\text{mod sin } \theta = 2[(0.25 \sin \theta + 0.25)^2 + 0.25 \sin \theta)].$$

The function is graphed in figure 5. The magnitude of mod sin $\theta$ ranges from 0.125 at 0° lat. to 0.53 at 30° lat. The lower limit, 0.125, is the value of the sin $\theta$ at 7.2°. Along with using an average geostrophic wind, as described above, the adjustment of the Coriolis parameter may be viewed as a further reduction of the steering wind relative to the true value at the position of the tropical cyclone center.

The steering section of the forecast program was written for operation on the Control Data Corporation's 1604 digital computer. Both NPGS and FNWF computers were utilized for these computations.

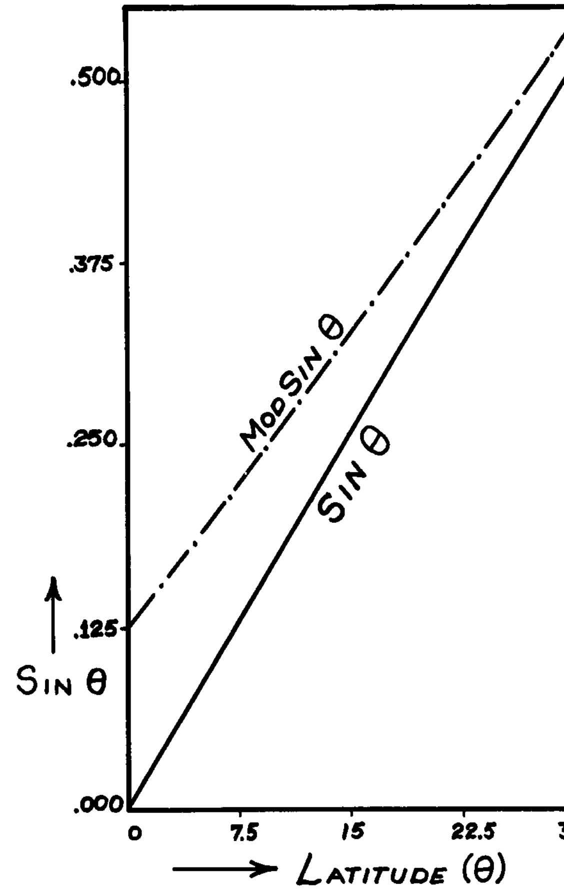



FIGURE 5.—Graph of sin $\theta$ and mod sin $\theta$ = $2[(0.25 \sin \theta + 0.25)^2 + 0.25 \sin \theta]$.

## 3. COMPOSITION OF THE TEST

Due to limited manpower and computer time, only those named North Pacific and North Atlantic tropical cyclones in existence during the period Aug. 15 to Nov. 1, 1965, were incorporated into the test. The sample included all 1965 Atlantic hurricanes and tropical storms (Anna, Betsy, Carol, Debbie, Elena) and 10 Pacific typhoons, (Lucy, Mary, Olive, Rose, Shirley, Trix, Virginia, Bess, Carmen, and Della). Only 0600 and 1800 GMT best track positions, as given in [8] and [10] were used, except for hurricane Carol, in which case 0000 and 1200 GMT positions were employed. Cyclone position forecasts, made in 1-hr. time steps, were printed out for each 12-hr. forecast interval up to 48 hr. and at 72 hr. Depression, tropical storm, hurricane/typhoon, and extratropical stages were included if the position was listed in the annual summaries. For the Atlantic area, 79 percent of the forecasts were made during storm and hurricane stages, 13 percent from depression, and 8 percent from extratropical stages. In the Pacific the vast majority, 98 percent, were from the storm/typhoon stages; the remainder, 2 percent, were depressions.

It is important to note that the *best track* cyclone positions were used in generating the forecasts up to 72 hr.

TABLE 1.—*1965, 12-hr. forecast errors in nautical miles. Number of forecasts in parentheses. Superscripts 1 and 2 indicate the relative merits of the two SR fields yielding the most accurate 12-hr. forecasts.*

| | Official | *SR* 1000 | *SR* 700 | *SR* 500 | *SR* 200 | *SR* 1000/500 | *SR* 1000/200 | *SR* 500/200 |
|---|---|---|---|---|---|---|---|---|
| *Hurricanes* | | | | | | | | |
| Anna | 119 (6) | $60^{1}$ (8) | $70^{2}$ (8) | 82 (6) | | 98 (6) | | |
| Betsy | 67 (57) | $78^{2}$ (29) | $74^{1}$ (32) | 83 (29) | 168 (32) | 96 (28) | 142 (29) | 172 (29) |
| Carol | 105 (38) | $93^{1}$ (31) | $94^{2}$ (30) | 127 (31) | 290 (31) | 101 (31) | 143 (31) | 171 (31) |
| Debbie | 65 (16) | $58^{2}$ (10) | $54^{1}$ (9) | 89 (10) | 209 (10) | 90 (10) | 167 (10) | 196 (10) |
| Elena | 114 (20) | 215 (13) | $170^{1}$ (14) | $194^{2}$ (13) | 306 (13) | 197 (13) | 217 (13) | 254 (13) |
| Average | 86 (137) | $99^{2}$ (91) | $93^{1}$ (93) | 115 (89) | 238 (86) | 112 (88) | 157 (83) | 187 (83) |
| *Typhoons* | | | | | | | | |
| Lucy | | $53^{1}$ (16) | 98 (16) | $84^{2}$ (12) | | 134 (11) | | |
| Mary | | $44^{2}$ (8) | 55 (8) | $28^{1}$ (7) | | 65 (7) | | |
| Olive | | $72^{2}$ (6) | 77 (8) | $61^{1}$ (6) | 115 (9) | 81 (6) | 122 (6) | 139 (6) |
| Rose | | 140 (10) | 117 (9) | $34^{1}$ (9) | 356 (9) | $78^{2}$ (9) | 168 (9) | 234 (9) |
| Shirley | | 140 (13) | 131 (13) | $122^{1}$ (13) | 146 (13) | $130^{2}$ (13) | 132 (13) | 134 (13) |
| Trix | | 134 (14) | 108 (15) | 97 (14) | $92^{2}$ (14) | 101 (14) | $81^{1}$ (14) | 111 (14) |
| Virginia | | 146 (6) | $108^{2}$ (7) | $104^{1}$ (6) | 181 (6) | 133 (6) | 192 (6) | 261 (6) |
| Bess | | 123 (14) | $81^{2}$ (12) | 84 (14) | 138 (14) | $75^{1}$ (14) | 130 (14) | 132 (14) |
| Carmen | | 131 (17) | 103 (16) | $67^{1}$ (17) | 95 (14) | $86^{2}$ (17) | 89 (14) | 93 (14) |
| Della | | 130 (12) | $100^{2}$ (13) | $85^{1}$ (12) | 136 (12) | 118 (12) | 134 (12) | 129 (12) |
| Average | 70 | 113 (116) | $100^{2}$(117) | $80^{1}$(110) | 147 (91) | $100^{2}$(109) | 124 (88) | 142 (88) |

using geostrophic steering winds computed from a single *SR* analysis dated at best track time plus 6 hr. Thus, in order to forecast the movement of a cyclone positioned at *I, J* (fig. 4) at 0600 GMT (1800 GMT) the analyzed *SR* field for 1200 GMT (0000 GMT) was used. However, in the case of Carol, initial hurricane position and *SR* steering flow were for the same synoptic time.

Although a different combination of the best track time and time of numerical analysis may have been more operationally realistic the major effort to this point was directed toward establishing the feasibility of using the *SR* field to derive a steering current. In addition, initial efforts were concentrated on the 12-hr. forecasts for which time mean *SR* steering winds are appropriate. From an operational point of view the *SR* analyses used in the test may be regarded as "perfect" 12-hr. *SR* prognostic fields initiated 6 hr. before warning time. Using *SR* analyses rather than prognoses to derive the steering current has the advantage that the forecast errors do not include contributions from the deficiences of a numerical prognostic model.

## 4. PRELIMINARY FINDINGS

Some of the preliminary findings which established the format for uniformly processing the forecast data to 72 hr. are important and will be outlined here. The initial experiments were designed to provide answers to the following questions:

a) Which *SR* field(s) will generate the most accurate forecasts considering both Atlantic and Pacific areas?

b) Does the forecast accuracy deteriorate as the forecast interval is increased to 72 hr.?

Table 1 indicates the average 12-hr. forecast errors (in n.mi.) for each cyclone which resulted from applying the numerical steering program (section 2) to *SR* fields from several selected isobaric levels (1000, 700, 500, 200 mb.) and layers (1000/500, 1000/200, 500/200 mb.). The official forecast errors from [8] and [10] are also shown. In the case of the Pacific cyclones the overall average official forecast error (70 n.mi.) was derived from a linear extrapolation of published error data at 24, 48, and 72 hr. Although a forecast for every 0600 and 1800 GMT best track position given in [8] and [10] was attempted, missing or unretrievable *SR* data disallowed some cases, especially those involving 200-mb. data.

Following are pertinent conclusions to be drawn from table 1:

a) Considering both oceans collectively, *SR* 500 performed best (i.e. least forecast error), *SR* 700 second best, and *SR* 1000/500 a close third.

b) In the Atlantic, on the average, *SR* 700 is best, followed by *SR* 1000 and *SR* 1000/500. The majority of individual cyclones (three out of five) behaved like the overall average.

c) In the Pacific, on the average, *SR* 500 is best, followed by *SR* 700 and *SR* 1000/500, each with similar results. The vast majority of storms (seven out of ten) behaved like the overall average.

d) *SR*s at the higher levels and layers (*SR* 200, *SR* 1000/200, and *SR* 500/200) generally yielded the poorest results.

e) Even considering the best numerical-steering result for the Atlantic (*SR* 700) and Pacific (*SR* 500), the official forecast accuracy is superior by more than 10 percent.

In view of the good performance of *SR* 500 in both oceans, this field was selected to test the feasibility of *SR* steering computations for forecast intervals out to 72 hr. Table 2 shows the result. Format of error data for this and most of the following tables is similar to table 1. Official 36-hr. errors (from [8] and [10]) are linear extrapolations from published error data at 24, 48, and 72 hr. in the Pacific and 12, 24, 48, and 72 hr. in the Atlantic. Table 3 aids in summarizing the results shown in table 2:

a) For each of the forecast time intervals tested, official results excel the NPGS steering system, except for 72 hr. in the Atlantic.

TABLE 2.—*1965, SR 500 forecast errors in nautical miles. Number of forecasts in parentheses*

| | 12 hr. | | 24 hr. | | 36 hr. | | 48 hr. | | 72 hr. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | *SR* | Official | *SR* | Official | *SR* | Official | *SR* | Official | *SR* | Official |
| *Hurricanes* | | | | | | | | | | |
| Anna | 82 (6) | 119 (6) | 149 (5) | 217 (4) | 234 (4) | | 322 (3) | | | |
| Betsy | 83 (29) | 67 (57) | 157 (28) | 130 (56) | 231 (27) | | 308 (26) | 273 (52) | 463 (24) | 469 (48) |
| Carol | 127 (31) | 105 (38) | 181 (30) | 192 (40) | 266 (29) | | 352 (28) | 355 (36) | 514 (26) | 448 (32) |
| Debbie | 89 (10) | 65 (16) | 149 (9) | 135 (14) | 220 (8) | | 287 (7) | 310 (8) | 390 (5) | 512 (6) |
| Elena | 194 (13) | 114 (20) | 353 (12) | 260 (20) | 493 (11) | | 510 (10) | 581 (16) | 705 (8) | 1104 (12) |
| Average | 115 (89) | 86(137) | 192 (84) | 171(134) | 279 (79) | 260 | 351 (74) | 346(112) | 509 (63) | 543 (98) |
| *Typhoons* | | | | | | | | | | |
| Lucy | 84 (12) | | 216 (11) | 169 (29) | 318 (10) | | 370 (11) | 329 (25) | 526 (9) | 481 (19) |
| Mary | 28 (7) | | 111 (6) | 107 (14) | 187 (5) | | 293 (4) | 154 (10) | 437 (3) | 170 (5) |
| Olive | 61 (6) | | 130 (5) | 138 (17) | | | 313 (3) | 284 (13) | 548 (2) | 449 (9) |
| Rose | 34 (9) | | 139 (8) | 55 (15) | 199 (7) | | 254 (6) | 127 (11) | 453 (4) | 245 (3) |
| Shirley | 122 (13) | | 231 (12) | 231 (16) | 335 (11) | | 425 (10) | 589 (12) | 591 (8) | 871 (3) |
| Trix | 97 (14) | | 187 (13) | 138 (27) | 275 (12) | | 348 (11) | 302 (23) | 401 (9) | 426 (18) |
| Virginia | 104 (6) | | 201 (5) | 289 (11) | 318 (4) | | 418 (3) | 615 (7) | 786 (2) | 1055 (3) |
| Bess | 84 (14) | | 120 (13) | 106 (26) | 173 (12) | | 229 (11) | 256 (22) | 360 (9) | 401 (16) |
| Carmen | 67 (17) | | 157 (16) | 148 (21) | 223 (15) | | 307 (14) | 238 (15) | 441 (12) | 289 (11) |
| Della | 85 (12) | | 197 (11) | 152 (23) | 286 (9) | | 366 (9) | 277 (17) | 550 (6) | 484 (11) |
| Average | 80(110) | 70 | 173(100) | 148(199) | 256 (85) | 225 | 331 (82) | 304(155) | 480 (64) | 440 (98) |

TABLE 3.—*1965, SR 500 forecast errors in nautical miles per hour of forecast interval*

| Forecast interval (hr.) | | 12 | 24 | 36 | 48 | 72 |
|---|---|---|---|---|---|---|
| *Hurricanes* | NPGS | 9.6 | 8.0 | 7.8 | 7.3 | 7.1 |
| | OFF | 7.2 | 7.1 | 7.2 | 7.2 | 7.5 |
| | NPGS-OFF | 2.4 | 0.9 | 0.6 | 0.1 | −0.4 |
| *Typhoons* | NPGS | 6.7 | 7.2 | 7.1 | 6.9 | 6.7 |
| | OFF | 5.8 | 6.2 | 6.2 | 6.3 | 6.1 |
| | NPGS-OFF | 0.9 | 1.0 | 0.9 | 0.6 | 0.6 |

TABLE 4.—*1965 SR 700 forecast errors in nautical miles. Number of forecasts in parentheses*

| Hurricanes | 12 hr. | 24 hr. | 36 hr. | 48 hr. | 72 hr. |
|---|---|---|---|---|---|
| Anna | 70 (8) | 127 (7) | 189 (6) | 284 (5) | 524 (3) |
| Betsy | 74 (32) | 141 (31) | 205 (30) | 273 (29) | 399(27) |
| Carol | 94 (30) | 183 (29) | 276 (28) | 363 (28) | 561(26) |
| Debbie | 54 (9) | 112 (9) | 173 (8) | 220 (7) | 261 (5) |
| Elena | 170 (14) | 328 (13) | 471 (12) | 595 (11) | 857 (9) |
| *SR* 700 average | 93 (93)<br>95 (87) | 178 (89)<br>183 (83) | 262 (84)<br>270 (78) | 345 (80)<br>348 (74) | 514(70)<br>516(63) |
| *SR* 500 average | 115 (89)<br>114 (87) | 192 (84)<br>191 (83) | 279 (79)<br>279 (78) | 351 (74) | 509(63) |
| Official average | 86(137) | 171(134) | 260 | 346(112) | 543(98) |

TABLE 5.—*1965 SR 500 forecast errors in nautical miles. Number of forecasts in parentheses*

| Typhoons | 12 hr. | 24 hr. |
|---|---|---|
| Lucy | 84 (12) | 216 (11) |
| Mary | 28 (7) | 111 (6) |
| Olive | 61 (6) | 130 (5) |
| Rose | 34 (9) | 139 (8) |
| Shirley | 122 (13) | 231 (12) |
| Trix | 97 (14) | 187 (13) |
| Virginia | 104 (6) | 201 (5) |
| Bess | 84 (14) | 120 (13) |
| Carmen | 67 (17) | 157 (16) |
| Della | 85 (12) | 197 (11) |
| *SR* 500 average | 80 (110)<br>80 (106) | 173(100)<br>168 (85) |
| *SR* 700 average | 100 (117)<br>102 (106) | 180 (92)<br>182 (85) |
| Official average | 70 | 148(199) |

b) The forecast error, in nautical miles per hour of forecast interval, generally decreased or held steady with time for the NPGS system, while the official error figure increased or held steady with time.

c) In a relative sense, the NPGS scheme shows improvement compared to the official out to 72 hr., especially in the Atlantic. This may be seen from the calculations of NPGS-OFFICIAL errors at each forecast interval.

A consideration of the results shown in tables 1–3 suggested continued and more extensive experimentation with the steering technique. However, before embarking on further testing and possible modification of the numerical scheme for periods out to 72 hr., some further, but limited, checks on the apparent merits of *SR* 700 in the Atlantic and *SR* 500 in the Pacific were attempted.

Due to the favorable performance of both *SR* 500 and *SR* 700, considering both oceans, and similarly good behavior of these levels from other but related forecast techniques [7], the two levels were intercompared at other than the 12-hr. forecast intervals.

Table 4 shows the relative merits of *SR* 700 and *SR* 500 for Atlantic forecasts up to a period of 72 hr. Error statistics are shown for all forecast data as well as for a homogeneous sample of forecast times. For example, 93 *SR* 700 and 89 *SR* 500 forecasts were possible for the 12-hr. interval while a maximum of 87 forecast times were common to the *SR* 500 and *SR* 700 computations. Results indicate the excellence of the *SR* 700 forecasts out to 48 hr. and *SR* 500 thereafter. The official forecast is superior to the optimal NPGS system in the Atlantic (i.e. *SR* 700) at 12 and 24 hr., while the official is worse than the optimal NPGS scheme at 72 hr. At 36 and 48 hr. official and NPGS accuracy are nearly equivalent.

Testing of the relative worth of *SR* 700 and *SR* 500 in the Pacific was limited to 12 and 24 hr. only (table 5). *SR* 500 maintained a lead in accuracy over *SR* 700 through 24 hr. but, as in the Atlantic, official forecast accuracy surpassed the NPGS *SR* 500 geostrophic-steering forecasts.

The preliminary findings displayed in tables 1–5 led to the decision to use *SR* 500 in the Pacific and *SR* 700 in

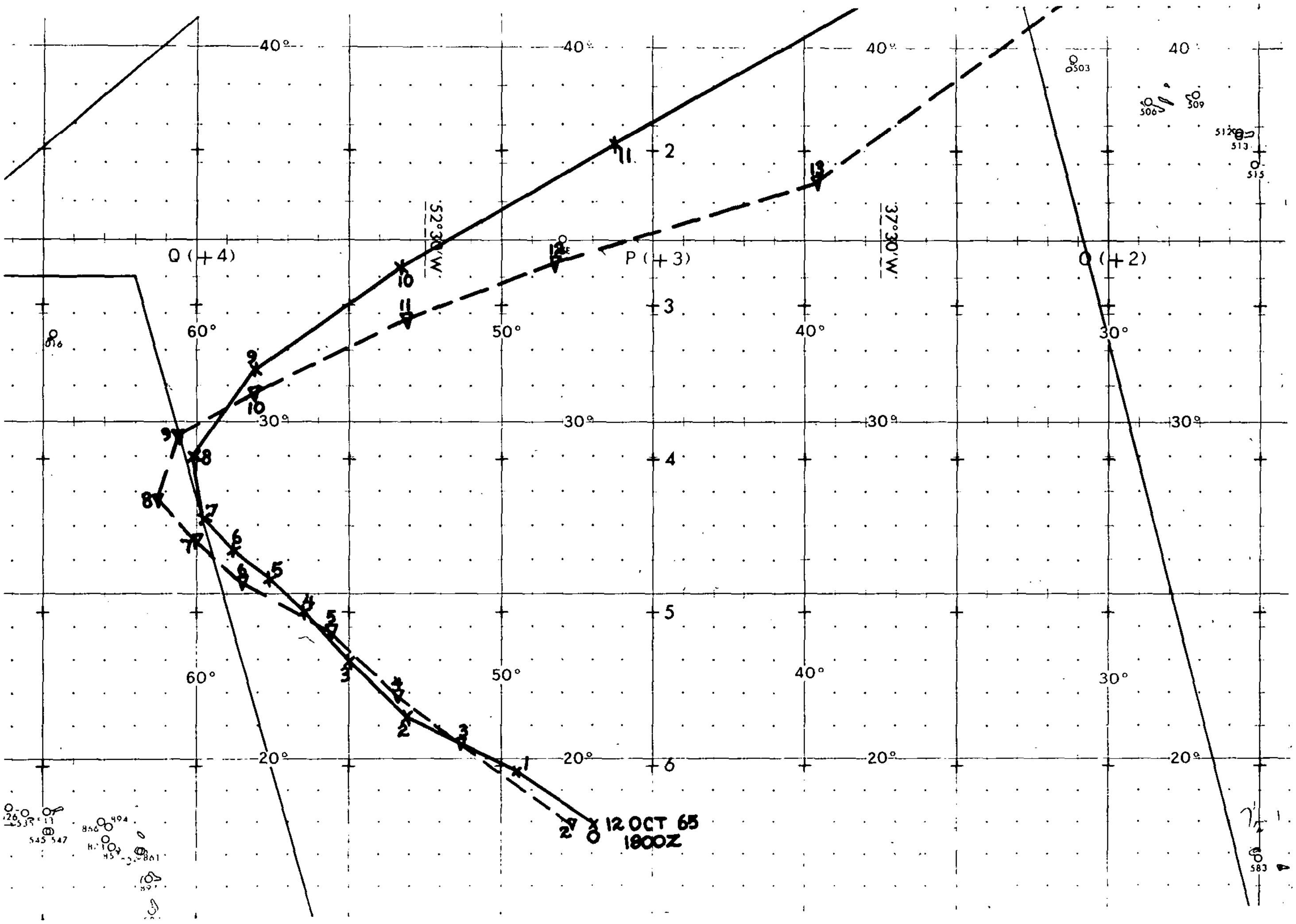



FIGURE 6.—Hurricane Elena positions at 12-hr. intervals, starting at 1800 GMT Oct. 12, 1965 (position "O"): best track (solid lines with crosses) and numerical-steering forecast track, $F_{24}$ (dashed line with triangles).

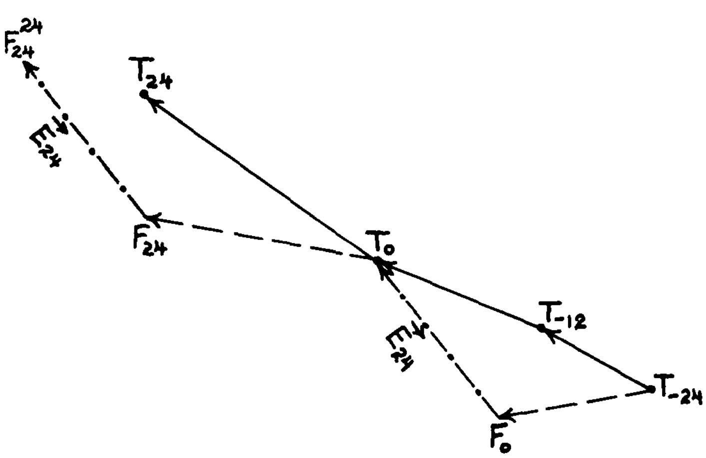



FIGURE 7.—Schematic example of a modified 24-hr. numerical-steering forecast (using $\vec{E}_{24}$) made from best track position $T_0$. In general, the vector correction for the bias in numerical steering, $\vec{E}_{yy}$, is for the same time period as the forecast interval implied by $F_{xx}$ and results in the modified position designated as $F_{xx}^{yy}$, where $yy=xx$.

the Atlantic, exclusively, for all subsequent testing of the numerical tropical cyclone steering scheme.

## 5. MODIFIED NPGS FORECAST SCHEME

A typical example of using the *SR* 700 geostrophic steering computation is shown in figure 6. The best track positions (from [10]) and the 24-hr. forecast positions, using numerical steering only, denoted by $F_{24}$, are plotted for hurricane Elena. Numbered positions on the best track are at 12-hr. intervals, starting with 1800 GMT, Oct. 12, 1965, which is labeled position "O". Corresponding numbers along the $F_{24}$ forecast track refer to the same times as those on the best track. For example, "5" on the best track is the cyclone-center position for 0600 GMT, Oct. 15, 1965, while position "5" along $F_{24}$ is the forecast cyclone-center position for the same time. Twenty-four-hr. forecast position "5" was generated from the best track position "3" at 0600 GMT, Oct. 14, 1965, using the *SR* 700 analysis at 1200 GMT, Oct. 14, 1965.

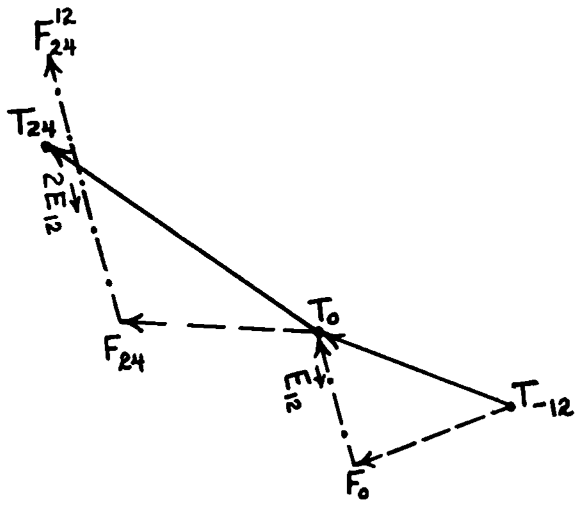



FIGURE 8.—Schematic example of a modified 24-hr. numerical-steering forecast (using $\vec{E}_{12}$) made from the best track position $T_0$. In general, the vector correction for bias in numerical steering is $\vec{E}_{12}$ × (forecast interval/12) and results in the modified position designated as $F^{12}_{xx}$.

Figure 6 indicates that the forecast and best tracks are similar in shape but positions at given times are not identical. This feature, common to most hurricanes and typhoons considered in this research, may be described as a consistent deficiency in both zonal and meridional components of the numerical-steering forecast. Thus, the vector error between forecast and best track positions represents a bias which may be used, with advantage, as a correction or modification to the subsequent numerical-steering forecasts.

Figure 7 schematically indicates the mechanics of applying one type of correction for the bias in the numerical-steering forecast ($F_{xx}$). For this figure and in the discussion which follows the subscripts associated with $T$ and $F$ (as, −12, 0, 12, 24, etc.) refer to time before or after "0", where "0" is the time at which the forecast in question is made (i.e. warning time). The solid lines connect the best track positions for −24, −12, 0 and 24 hr., while $F_0$ and $F_{24}$ indicate the 24-hr. numerical forecast positions. $\vec{E}_{24}$ is the vector error of the 24-hr. forecast made from the $T_{-24}$ position. This forecast error, known at time "0," is then employed as a correction to the 24-hr. forecast made at time "0." Such a procedure generates *modified* numerical forecast positions, as $F^{24}_{24}$ in figure 7. The superscripts on $F$, as used in figure 7, and in the text, figures, and tables that follow refer to the forecast interval from which the correction for numerical-forecast bias was selected. Hence, superscript "24" refers to use of the most recent 24-hr. numerical forecast error as a correction to the numerical-steering forecast made at time "0." Applied to a 48-hr. forecast, the scheme symbolized in figure 7 yields a modified forecast position designated $F^{48}_{48}$. It is to be noted that as the forecast interval increases so does the necessary time lag for application increase. Thus, in order to make a modified 72-hr. forecast one 72-hr. forecast period must pass before $\vec{E}_{72}$ is known. This limits quite severely the totality of application in the forecasting of tropical cyclones.

In view of the difficulty just mentioned, a scheme similar to that shown in figure 7 was developed, but in this case only the most recent 12-hr. numerical forecast errors were used, regardless of forecast interval. Figure 8 shows a modified 24-hr. forecast made at time "0" employing numerical steering, $F_{24}$, plus a correction for bias, $2\vec{E}_{12}$. The modified forecast position is designated $F^{12}_{24}$. When applied to a 48-hr. (72-hr.) forecast the modified forecast position is $F^{12}_{48}$ ($F^{12}_{72}$) and $4\vec{E}_{12}(6\vec{E}_{12})$ is the appropriate vector correction for bias.

The two modes of modifications just outlined are applied to 24-hr. forecasts of Elena and are shown in figure 9. It is obvious that the modified forecasts result in cyclone-position forecasts superior to $F_{24}$ with the $F^{12}_{24}$ scheme best.

For forecast intervals beyond 12 and 24 hr., two other modification schemes, involving the bias correction, were used. Figures 10 and 11 indicate these modes as applied to 36-hr. forecasts made at time "0." The scheme in figure 10 is exactly like that in figure 8 only 24- rather than 12-hr. values of $\vec{E}$ are employed. Figure 11 shows a scheme for which the most recent 12- and 24-hr. numerical forecast errors are used, the former weighted twice that of the latter.

Examples of the type of modifications portrayed in figures 10 and 11 are shown in figure 12 for 48-hr. forecasts of typhoon Carmen. Though not entirely obvious at this point, the $F^{24}_{48}$ system gives the optimal forecast track for Carmen.

Each one of the adjustment schemes described in figures 7, 8, 10, and 11 was applied to each Pacific typhoon for every possible 0600 and 1800 GMT forecast time while application to Atlantic tropical storms and hurricanes was somewhat more limited. Tables 6 to 16 give the basic results using *SR* 500 in the Pacific and *SR* 700 in the Atlantic. Wherever possible, averages for homogeneous sets of forecast data are shown. In the case of official forecasts, such comparisons are limited due to different forecast times in the Atlantic (04, 10, 16, 22 GMT) and the availability of individual official forecasts for 24 and 48 hr. only in the Pacific. Various aspects of these error statistics are summarized below:

12 hr.: Atlantic (table 6): The modified forecasts ($F^{12}_{12}$) represent a 48 percent improvement over the $F_{12}$ forecasts as well as significantly excelling the accuracy of the official forecasts. This is true for the overall average and for each individual storm.

Pacific (table 7): The situation in the Pacific is similar to the Atlantic with $F^{12}_{12}$ representing a 34 percent improvement relative to $F_{12}$ and a 23 percent increase in accuracy over the estimated official forecast score.

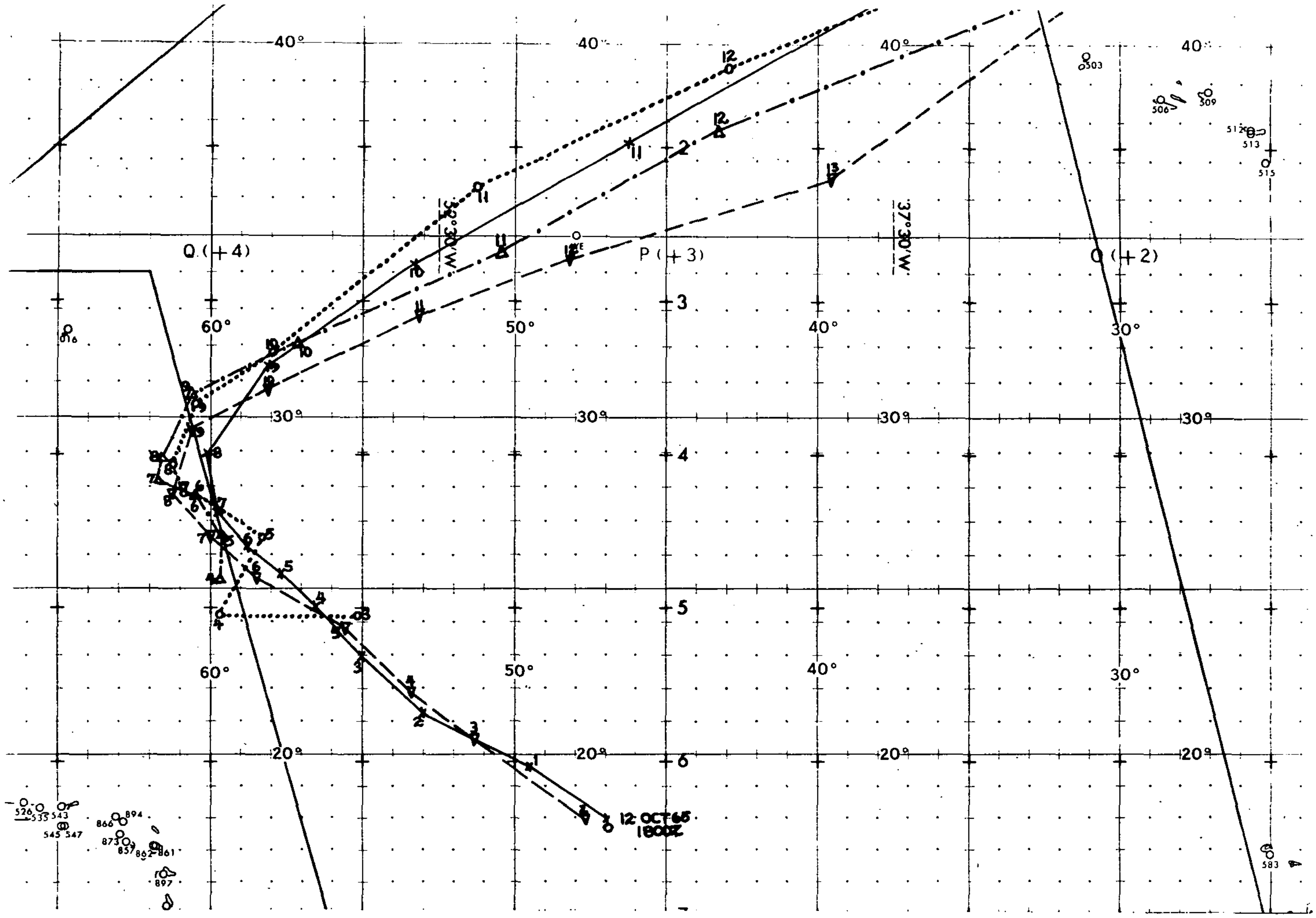



FIGURE 9.—Same as figure 6 with the addition of forecast tracks $F_{24}^{24}$ (dash-dot line with triangles) and $F_2^1$ (dotted line with circles).

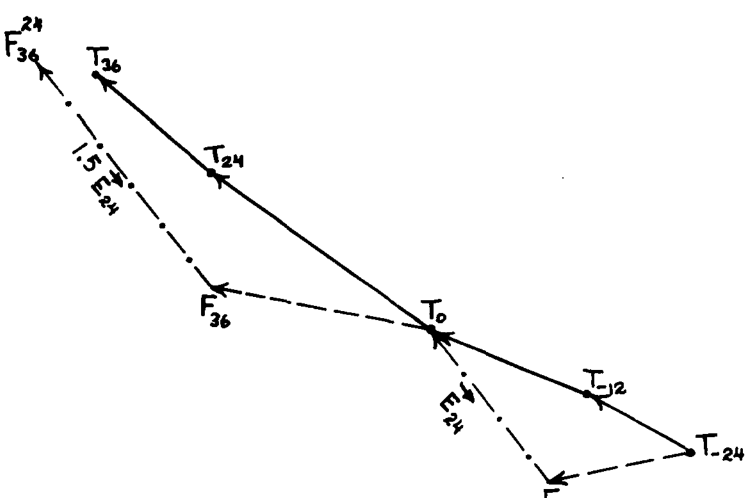



FIGURE 10.—Schematic example of a modified 36-hr. numerical-steering forecast (using $\vec{E}_{24}$) made from best track position $T_0$. In general, the vector correction for bias in numerical steering is $\vec{E}_{24}\times$(forecast interval/24) and results in the modified position designated as $F_{xx}^{24}$.

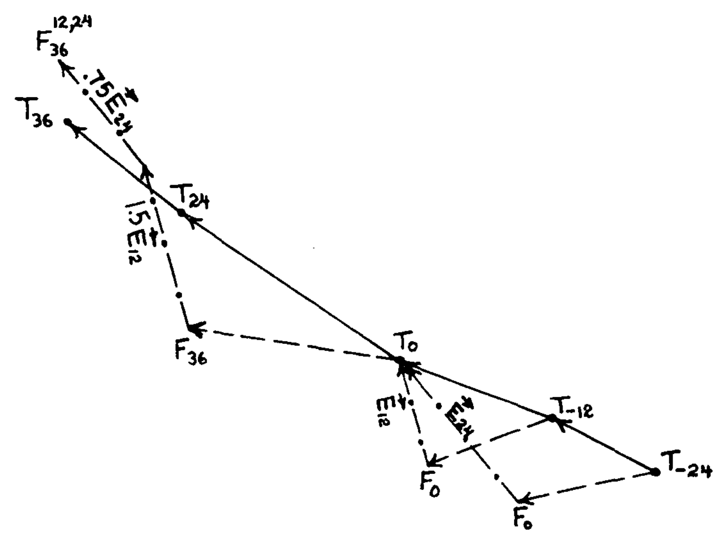



FIGURE 11.—Schematic example of a modified 36-hr. numerical-steering forecast (using $\vec{E}_{12}$ and $\vec{E}_{24}$) made from the best track position $T_0$. In general, the vector correction for bias in numerical steering is $A\vec{E}_{12}+B\vec{E}_{24}$ where $A$=forecast interval/24 and $B$=0.5 A, and results in the modified position designated as $F_{xx}^{12,24}$.

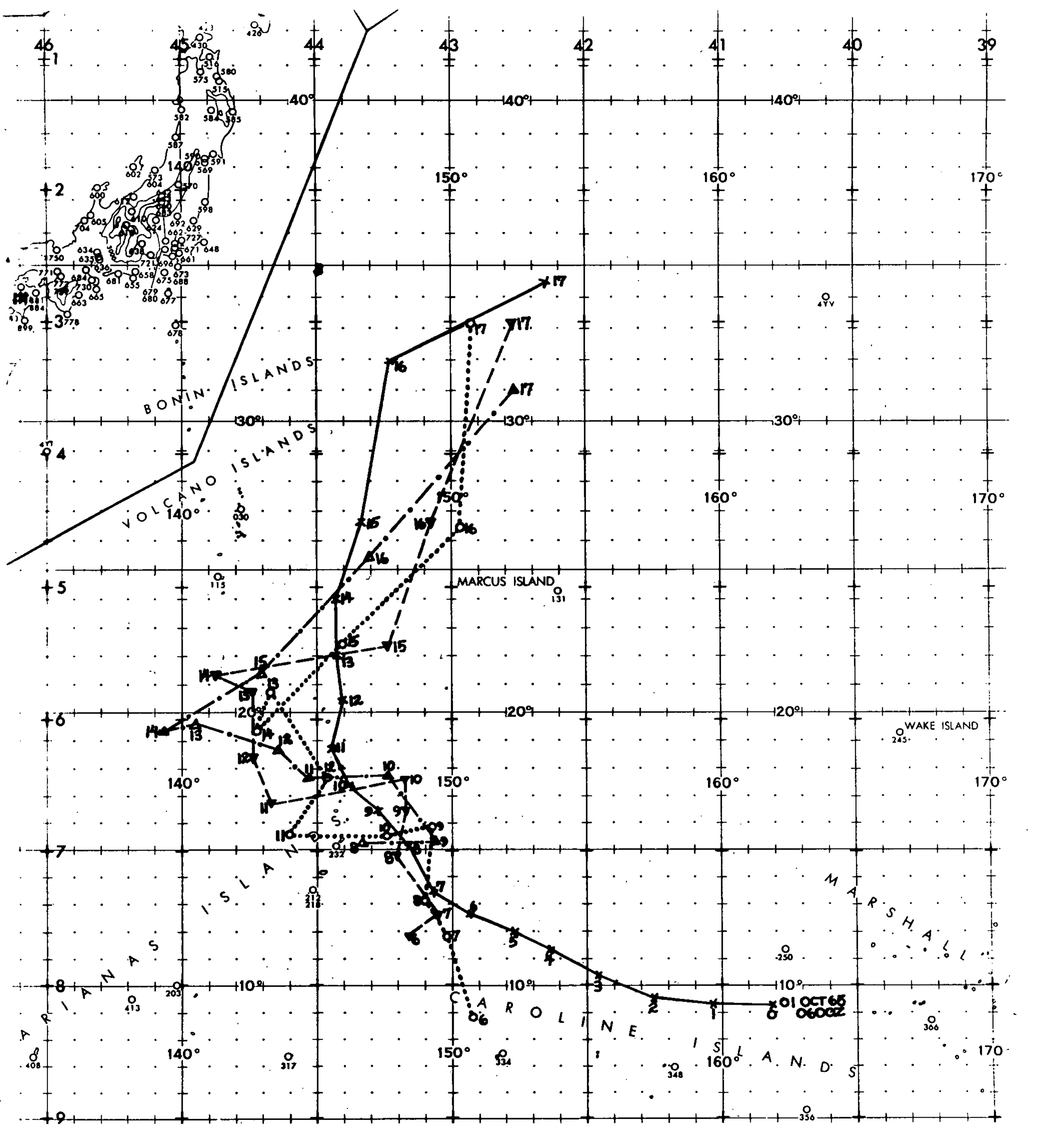



FIGURE 12.—Typhoon Carmen positions at 12-hr. intervals, starting with 0600 GMT, Oct. 1, 1965 (position "O"): best track (solid line with crosses) and modified numerical-steering forecast tracks, $F_{48}^{48}$ (dash-dot line with triangles), $F_{48}^{24}$ (dashed line with triangles), and $F_{48}^{12,\,24}$ (dotted line with circles).

TABLE 6.—*1965, 12-hr. forecast errors in nautical miles. Number of forecasts in parentheses*

| Hurricanes | Official | *SR* 700 mb. $F_{12}$ | *SR* 700 mb. $F_{12}^{12}$ |
|---|---|---|---|
| Anna | 119 (6) | 70 (8) | 47 (7) |
| Betsy | 67 (57) | 74 (32) | 45 (31) |
| Carol | 105 (38) | 94 (30) | 42 (28) |
| Debbie | 65 (16) | 54 (9) | 28 (8) |
| Elena | 114 (20) | 170 (14) | 71 (13) |
| Average | 86 (137) | 93 (93) | 47 (87) |
| | | 91 (87) | 47 (87) |

24 hr.: Atlantic (table 8): The 12-hr. numerical-steering forecast bias is most significant for the 24-hr. forecast, a not unexpected result in view of the relation of $F_{12}^{12}$ to $F_{12}$. Again the official forecast error is considerably greater than that of the NPGS optimal scheme, namely $F_{24}^{12}$.

Pacific (table 9): Unlike the Atlantic, application of the 24-hr. bias correction yields the optimal scheme, $F_{24}^{24}$, with the official forecast error, 150 n.mi., in considerable excess of the 108-n.mi. error for a homogeneous sample of 61 $F_{24}^{24}$ forecasts. Every cyclone, except Rose, shows the $F_{24}^{24}$ error less than the official figure.

TABLE 7.—*1965, 12-hr. forecast errors in nautical miles. Number of forecasts in parentheses*

| Typhoons | Official | SR 500 mb. | |
|---|---|---|---|
| | | $F_{12}$ | $F_{12}^{12}$ |
| Lucy | | 84 (12) | 60 (8) |
| Mary | | 28 (7) | 41 (5) |
| Olive | | 61 (6) | 46 (4) |
| Rose | | 34 (9) | 43 (8) |
| Shirley | | 122 (13) | 53 (12) |
| Trix | | 97 (14) | 52 (12) |
| Virginia | | 104 (6) | 51 (4) |
| Bess | | 84 (14) | 54 (13) |
| Carmen | | 67 (17) | 62 (16) |
| Della | | 85 (12) | 63 (10) |
| Average | 70 | 80(110)<br>82 (92) | 54 (92)<br>54 (92) |

TABLE 8.—*1965, 24-hr. forecast errors in nautical miles. Number of forecasts in parentheses*

| Hurricanes | Official | SR 700 mb. | | |
|---|---|---|---|---|
| | | $F_{24}$ | $F_{24}^{12}$ | $F_{24}^{24}$ |
| Anna | 217 (4) | 127 (7) | 127 (6) | 126 (5) |
| Betsy | 130 (56) | 141 (31) | 110 (30) | 114 (29) |
| Carol | 192 (40) | 183 (29) | 108 (27) | 117 (26) |
| Debbie | 135 (14) | 112 (9) | 72 (8) | 99 (7) |
| Elena | 260 (20) | 328 (13) | 182 (12) | 226 (11) |
| Average | 171 (134) | 178 (89)<br>174 (83)<br>173 (77) | 117 (83)<br>117 (83)<br>119 (77) | 130 (78)<br><br>128 (77) |

TABLE 9.—*1965, 24-hr. forecast errors in nautical miles. Number of forecasts in parentheses*

| Typhoons | Official | SR 500 mb. | | |
|---|---|---|---|---|
| | | $F_{24}$ | $F_{24}^{12}$ | $F_{24}^{24}$ |
| Lucy | 169 (29) | 216 (11) | 133 (8) | 107 (7) |
| Mary | 107 (14) | 111 (6) | 136 (4) | 95 (3) |
| Olive | 138 (17) | 130 (5) | 56 (3) | 124 (1) |
| Rose | 55 (15) | 139 (8) | 147 (7) | 58 (6) |
| Shirley | 231 (16) | 231 (12) | 139 (11) | 163 (10) |
| Trix | 138 (27) | 187 (13) | 106 (11) | 118 (10) |
| Virginia | 289 (11) | 201 (5) | 173 (3) | 94 (2) |
| Bess | 106 (26) | 120 (13) | 124 (12) | 85 (11) |
| Carmen | 148 (21) | 157 (16) | 134 (15) | 89 (14) |
| Della | 152 (23) | 197 (11) | 153 (9) | 145 (8) |
| Average | 148 (199)<br>155 (90)<br>154 (76)<br>150 (61) | 173 (100)<br>177 (90)<br>177 (76)<br>181 (61) | 131 (83)<br><br>131 (76)<br>134 (61) | 109 (72)<br><br><br>108 (61) |

36 hr.: Atlantic (table 10): Although all three schemes equal or surpass the extrapolated official forecast accuracy, $F_{36}^{12}$ is optimum, again emphasizing the importance of the most recent history. Anna provides a minor exception to this trend.

Pacific (table 11): The importance of the 24-hr. forecast to the modified 36-hr. forecasts is seen from the performance of $F_{36}^{24}$ with an average error of 170 n.mi. (63 cases) compared to 225 n.mi. for the official forecasts.

48 hr.: Atlantic (table 12): At this point in the range of forecast intervals considered, a correction for bias taken from the same interval as the forecast (i.e. 48 hr.) is detrimental. That is, the errors using $F_{48}^{48}$ are greater than for $F_{48}$. The $F_{xx}^{12}$ scheme continues to be best while the official and optimal NPGS schemes are producing results quantitatively more similar than for shorter forecast periods.

Pacific (table 13): The Pacific sample continues to behave differently than the Atlantic with the most complex modification, $F_{48}^{12,24}$, yielding the best forecast accuracy, although all four types of bias corrections improve upon $F_{48}$. The official forecast continues to be excelled by the optimal NPGS scheme.

72 hr.: Atlantic (table 14): Comments for the Atlantic at 48 hr. are true for the 72-hr. forecast interval as well except that bias corrections of any type considered did not improve upon $F_{72}$. However, official forecast accuracy is still surpassed, namely by $F_{72}$.

Pacific (table 15): This is the most difficult table to interpret since the averages for nonhomogeneous

TABLE 10.—*1965, 36-hr. forecast errors in nautical miles. Number of forecasts in parentheses*

| Hurricanes | Official | SR 700 mb. | | |
|---|---|---|---|---|
| | | $F_{36}$ | $F_{36}^{12}$ | $F_{36}^{36}$ |
| Anna | | 189 (6) | 215 (5) | 246 (3) |
| Betsy | | 205 (30) | 198 (29) | 220 (27) |
| Carol | | 276 (28) | 195 (26) | 217 (25) |
| Debbie | | 173 (8) | 122 (7) | 202 (5) |
| Elena | | 471 (12) | 338 (11) | 431 (9) |
| Average | 260 | 262 (84)<br>259 (78)<br>260 (68) | 211 (78)<br>211 (78)<br>215 (68) | 246 (69)<br><br>244 (68) |

TABLE 11.—*1965, 36-hr. forecast errors in nautical miles. Number of forecasts in parentheses*

| Typhoons | Official | SR 500 mb. | | | | |
|---|---|---|---|---|---|---|
| | | $F_{36}$ | $F_{36}^{12}$ | $F_{36}^{24}$ | $F_{36}^{12,24}$ | $F_{36}^{36}$ |
| Lucy | | 318 (10) | 181 (7) | 162 (6) | 152 (4) | 130 (5) |
| Mary | | 187 (5) | 266 (3) | 174 (3) | 226 (2) | 152 (2) |
| Olive | | | | | | |
| Rose | | 199 (7) | 213 (6) | 92 (5) | 141 (5) | 100 (4) |
| Shirley | | 335 (11) | 256 (10) | 278 (9) | 270 (9) | 308 (8) |
| Trix | | 275 (12) | 197 (10) | 215 (9) | 180 (8) | 236 (8) |
| Virginia | | 318 (4) | 341 (2) | 270 (2) | 252 (1) | 329 (1) |
| Bess | | 173 (12) | 194 (11) | 139 (10) | 146 (10) | 137 (9) |
| Carmen | | 223 (15) | 385 (14) | 126 (13) | 149 (13) | 145 (12) |
| Della | | 286 (9) | 174 (7) | 128 (6) | 104 (5) | 142 (5) |
| Average | 225 | 256 (85)<br>255 (70)<br>259 (57)<br>259 (57)<br>257 (44) | 247 (70)<br>247 (70)<br>251 (57)<br>251 (57)<br>255 (44) | 170 (63)<br><br>162 (57)<br>162 (57)<br>152 (44) | 172 (57)<br><br><br>172 (57)<br>163 (44) | 180 (54)<br><br><br><br>169 (44) |

TABLE 12.—*1965, 48-hr. forecast errors in nautical miles. Number of forecasts in parentheses*

| Hurricanes | Official | SR 700 mb. | | |
|---|---|---|---|---|
| | | $F_{48}$ | $F_{48}^{12}$ | $F_{48}^{48}$ |
| Anna | ------- | 284 (5) | 304 (4) | 432 (1) |
| Betsy | 273 (52) | 273 (29) | 313 (28) | 353 (25) |
| Carol | 355 (36) | 363 (28) | 319 (27) | 349 (24) |
| Debbie | 310 (8) | 220 (7) | 198 (6) | 315 (3) |
| Elena | 581 (16) | 595 (11) | 478 (10) | 695 (7) |
| Average | 346(112) | 345 (80)<br>341 (75)<br>349 (60) | 327 (75)<br>327 (75)<br>346 (60) | 391 (60)<br><br>391 (60) |

TABLE 13.—*1965, 48-hr. forecast errors in nautical miles. Number of forecasts in parentheses*

| Typhoons | Official | SR 500 mb. | | | | |
|---|---|---|---|---|---|---|
| | | $F_{48}$ | $F_{48}^{12}$ | $F_{48}^{24}$ | $F_{48}^{12,24}$ | $F_{48}^{48}$ |
| Lucy | 329 (25) | 370 (11) | 276 (8) | 243 (7) | 223 (5) | 267 (6) |
| Mary | 154 (10) | 293 (4) | 364 (3) | 190 (2) | 284 (2) | |
| Olive | 284 (13) | 313 (3) | 73 (1) | | | 115 (1) |
| Rose | 127 (11) | 254 (6) | 242 (5) | 117 (4) | 173 (4) | 128 (2) |
| Shirley | 589 (12) | 425 (10) | 383 (9) | 379 (8) | 364 (8) | 419 (6) |
| Trix | 302 (23) | 348 (11) | 299 (9) | 319 (8) | 261 (7) | 438 (7) |
| Virginia | 615 (7) | 418 (3) | 488 (2) | 298 (1) | 374 (1) | |
| Bess | 256 (22) | 229 (11) | 278 (10) | 240 (9) | 219 (9) | 211 (7) |
| Carmen | 238 (15) | 307 (14) | 267 (13) | 187 (12) | 212 (12) | 263 (10) |
| Della | 277 (17) | 366 (9) | 273 (7) | 214 (6) | 200 (5) | 170 (4) |
| Average | 304 (155) | 331 (82) | 296 (67) | 248 (57) | 245 (53) | 287 (43) |
| | 311 (70) | 343 (70) | | | | |
| | 310 (59) | 342 (59) | 300 (59) | | | |
| | 314 (45) | 346 (45) | 293 (45) | 253 (45) | | |
| | 314 (45) | 346 (45) | 293 (45) | 253 (45) | 250 (45) | |
| | 338 (32) | 341 (32) | 285 (32) | 264 (32) | 253 (32) | 282 (32) |

TABLE 14.—*1965, 72-hr. forecast errors in nautical miles. Number of forecasts in parentheses*

| Hurricanes | Official | SR 700 mb. | | | |
|---|---|---|---|---|---|
| | | $F_{72}$ | $F_{72}^{12}$ | $F_{72}^{24}$ | $F_{72}^{72}$ |
| Anna | | 524 (3) | 574 (2) | 798 (1) | |
| Betsy | 469 (48) | 399 (27) | 564 (26) | 563 (25) | 553 (21) |
| Carol | 448 (32) | 561 (26) | 571 (25) | 564 (24) | 658 (20) |
| Debbie | 512 (6) | 261 (5) | 239 (4) | 222 (3) | |
| Elena | 1104 (12) | 857 (9) | 888 (8) | 1004 (7) | 1395 (3) |
| Average | 543 (98) | 514 (70) | 587 (65) | 602 (60) | 658 (44) |
| | | 512 (65) | 587 (65) | | |
| | | 517 (60) | 602 (60) | 602 (60) | |

sets of forecast data suggest $F_{72}^{12,24}$ is best while the homogeneous sets of data indicate $F_{72}^{24}$ is optimum. But, since the number of cases is relatively small for the homogeneous sets, the latter figures cannot be regarded as significant.

Summarizing information for tables 6–15 is shown in table 16. The forecast error per unit of time, using the optimal NPGS scheme, increases with time, particularly so in the Atlantic. However, the NPGS system always surpasses the official forecast accuracy although the ratio generally decreases with increasing time. In addition, table 16 gives information on the distribution of NPGS forecast errors, using the optimal scheme. In the Altantic, on the average, about ⅔ (½) of the forecast errors lie within 3 kt. of the average forecast error through 36 (for 48 and 72) hr. The dispersion of errors is considerably less in the Pacific where ¾ (⅔) represents the corresponding number of cases for 12, 24, and 36 (48 and 72) hr. Considering both oceans, the remaining ⅓ of the cases are about evenly distributed between the very large (greater than average-plus-3 kt.) and very small (less than average-minus-3 kt.) forecast errors. It is also evident from the listing of optimal schemes that the short-term peculiarities (i.e. 12, 24 hr.) in cyclone trajectories have long-term application (up to 72 hr.) in the modified forecast procedure.

Figures 13 and 14 show Atlantic and Pacific examples of forecasts to 72 hr., each made from a given synoptic

TABLE 15.—*1965, 72-hr. forecast errors in nautical miles. Number of forecasts in parentheses*

| Typhoons | Official | SR 500 mb. | | | | |
|---|---|---|---|---|---|---|
| | | $F_{72}$ | $F_{72}^{12}$ | $F_{72}^{24}$ | $F_{72}^{12,24}$ | $F_{72}^{72}$ |
| Lucy | 481 (19) | 526 (9) | 332 (6) | 444 (5) | 308 (3) | 705 (3) |
| Mary | 170 (5) | 437 (3) | 518 (2) | 187 (1) | 365 (1) | |
| Olive | 449 (9) | 548 (2) | 132 (1) | | | |
| Rose | 245 (3) | 453 (4) | 431 (3) | 148 (2) | 268 (2) | |
| Shirley | 871 (3) | 591 (8) | 562 (7) | 532 (6) | 535 (6) | 474 (2) |
| Trix | 426 (18) | 401 (9) | 376 (7) | 508 (7) | 367 (6) | 706 (3) |
| Virginia | 1055 (3) | 786 (2) | 690 (1) | | | |
| Bess | 401 (16) | 360 (9) | 501 (8) | 323 (7) | 360 (7) | 265 (3) |
| Carmen | 289 (11) | 441 (12) | 466 (11) | 329 (10) | 397 (10) | 516 (6) |
| Della | 484 (11) | 550 (6) | 294 (4) | 237 (4) | 203 (3) | 42 (1) |
| Average | 440 (98) | 480 (64) | 440 (50) | 380 (42) | 377 (38) | 506 (18) |
| | | 458 (50) | 440 (50) | | | |
| | | 463 (38) | 446 (38) | 354 (38) | 377 (38) | |
| | | 463 (38) | 446 (38) | 354 (38) | 377 (38) | |
| | | 483 (14) | 552 (14) | 481 (14) | 504 (14) | 473 (14) |

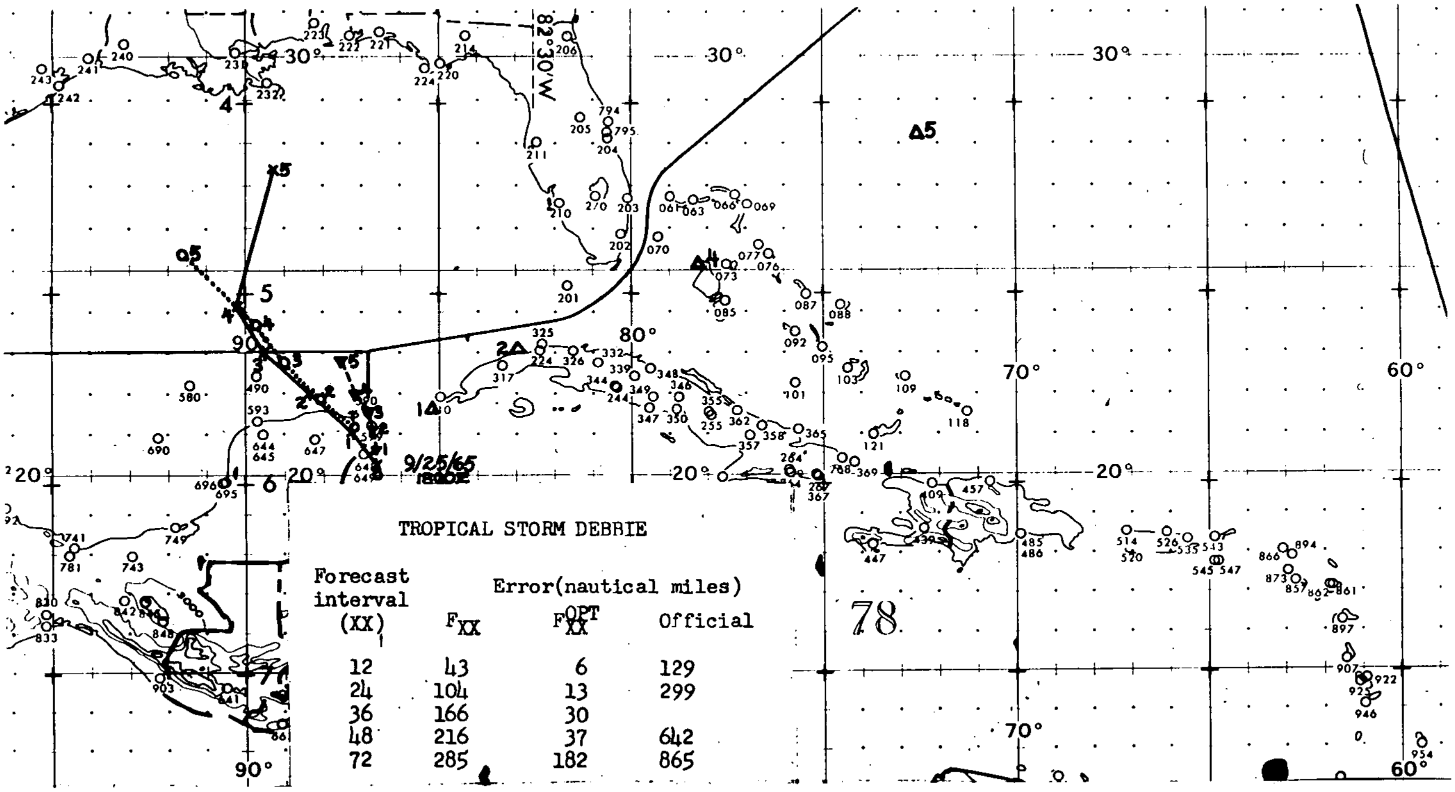
TABLE 16.—*Highlights of the evaluation of the optimal NPGS forecast scheme*

| | Forecast interval (hr.) | Optimal NPGS scheme | Avg. NPGS error (n.mi./hr. of fcst. interval) | % NPGS errors within: 1 kt. of ave. | 2 kt. of ave. | 3 kt. of ave. | Official optimal NPGS error |
|---|---|---|---|---|---|---|---|
| Atlantic | 12 | $F_{12}^{12}$ | 3.9 | 30 | 56 | 76 | 1.8 |
| | 24 | $F_{24}^{12}$ | 4.9 | 23 | 46 | 64 | 1.4 |
| | 36 | $F_{36}^{12}$ | 5.9 | 22 | 42 | 60 | 1.2 |
| | 48 | $F_{48}^{12}$ | 6.8 | 18 | 40 | 55 | 1.1 |
| | 72 | $F_{72}$ | 7.1 | 17 | 34 | 50 | 1.1 |
| Pacific | 12 | $F_{12}^{12}$ | 4.5 | 28 | 60 | 82 | 1.3 |
| | 24 | $F_{24}^{24}$ | 4.5 | 34 | 51 | 74 | 1.5 |
| | 36 | $F_{36}^{24}$ | 4.7 | 30 | 54 | 69 | 1.2 |
| | 48 | $F_{48}^{12,24}$ | 5.1 | 21 | 46 | 64 | 1.2 |
| | 72 | $F_{72}^{12,24}$ | 5.2 | 21 | 41 | 62 | 1.2 |

time. The best track, the NPGS numerical-steering forecast track ($F_{xx}$) and the optimal NPGS forecast track ($F_{xxx}^{opt}$) are shown for the two cases portrayed. Additionally, the available official forecast positions are indicated. The inadequacy of the numerical-steering forecast relative to the modified forecast is clearly indicated in both the Debbie and Rose figures. The reasonable continuity of successive forecast positions, 12 to 72 hr., using the optimal scheme is evident. The extreme disparity which may occur between the official and the modified numerical schemes is also shown in the case of Debbie.

## 6. NHC-64 VS. NPGS OPTIMAL FORECAST SCHEME

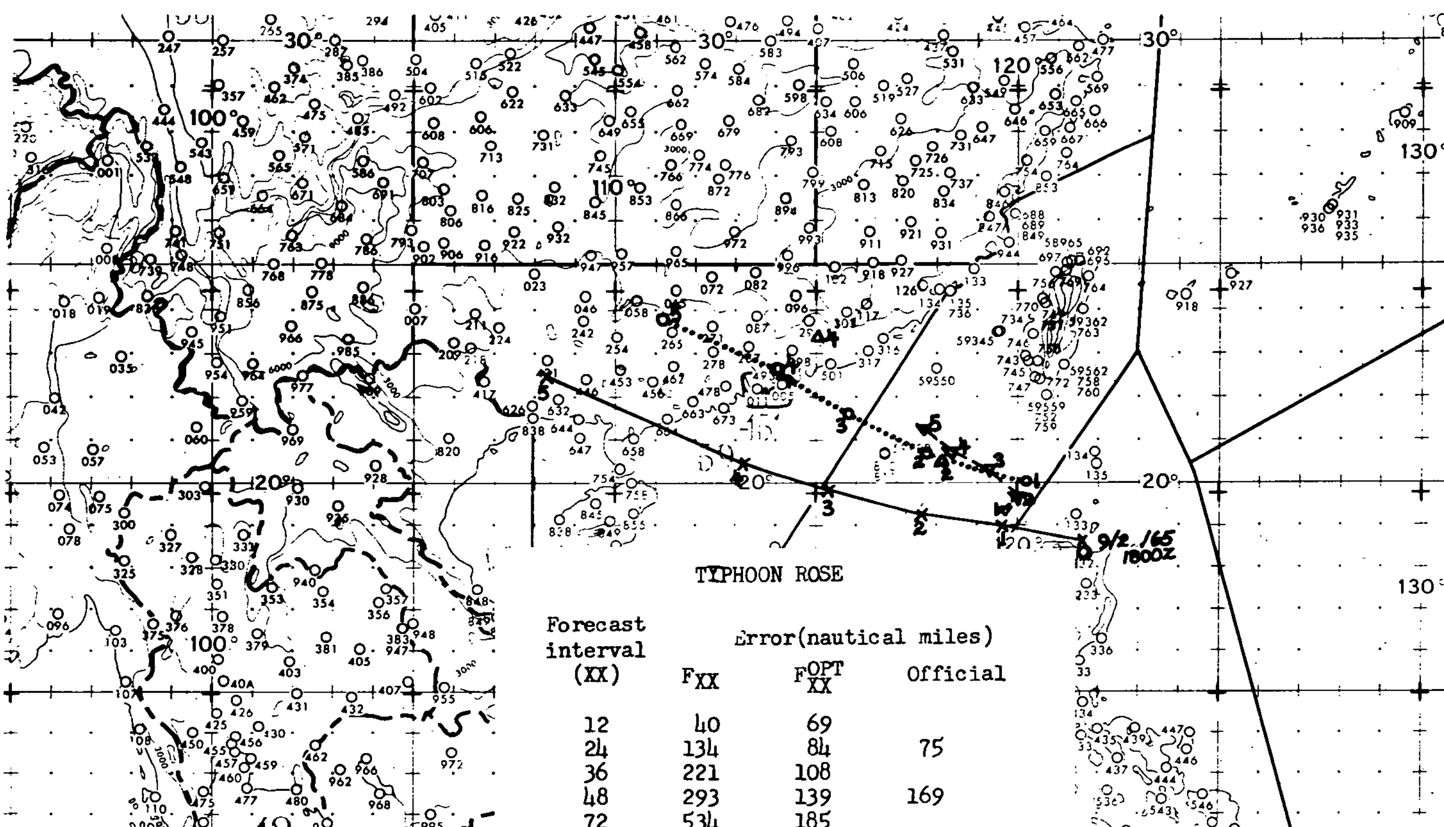
A further evaluation of the NPGS forecast errors was made through an intercomparison with the NHC-64 statistical technique [5, 6, 7] as developed by the National Hurricane Research Laboratory, Miami, Fla. Table 17 shows results for 12-, 24-, 36-, and 48-hr. forecasts. Since the NHC-64 forecasts were made at 0000 and 1200 GMT, an average of the errors from 0600 and 1800 GMT optimal NPGS forecasts were compared to each NHC-64 forecast considered. This is the closest approach to homogeneity that could be made here. Carol is an exception, since 0000 and 1200 GMT NPGS forecasts were computed making this storm's sample truly homogeneous with the NHC-64




TROPICAL STORM DEBBIE

| Forecast interval (XX) | Error (nautical miles) $F_{XX}$ | $F_{XX}^{OPT}$ | Official |
|---|---|---|---|
| 12 | 43 | 6 | 129 |
| 24 | 104 | 13 | 299 |
| 36 | 166 | 30 | |
| 48 | 216 | 37 | 642 |
| 72 | 285 | 182 | 865 |

FIGURE 13.—Tropical storm Debbie. 12-, 24-, 36-, 48-, and 72-hr. forecasts made at 1800 GMT, Sept. 25, 1965, using the numerical-steering computation ($F_{xx}$) (dashed line with triangles), and optimal scheme ($F_{xx}^{opt}$) (dotted line with circles). Best track (solid line with crosses) and available official forecast positions (Δ) are shown.




TYPHOON ROSE

| Forecast interval (XX) | Error (nautical miles) $F_{XX}$ | $F_{XX}^{OPT}$ | Official |
|---|---|---|---|
| 12 | 40 | 69 | |
| 24 | 134 | 84 | 75 |
| 36 | 221 | 108 | |
| 48 | 293 | 139 | 169 |
| 72 | 534 | 185 | |

FIGURE 14.—Typhoon Rose. Forecasts made at 1800 GMT, Sept. 2, 1965. Remainder of legend as in figure 13.

TABLE 17.—*Forecast errors: NHC-64 vs. NPGS-67 in nautical miles. Number of forecasts in parentheses*

| Hurricanes | 12 hr. | | 24 hr. | | 36 hr. | | 48 hr. | |
|---|---|---|---|---|---|---|---|---|
| | NHC-64 | NPGS ($F^{12}_{12}$) | NHC-64 | NPGS ($F^{12}_{24}$) | NHC-64 | NPGS ($F^{12}_{36}$) | NHC-64 | NPGS ($F^{12}_{48}$) |
| Anna | | | | | | | | |
| Betsy | 49 (24) | 40 (24) | 80 (19) | 109 (19) | 143 (21) | 187 (21) | 186 (20) | 306 (20) |
| Carol | 117 (15) | 39 (15) | 143 (14) | 102 (14) | 215 (15) | 200 (15) | 302 (15) | 269 (15) |
| Debbie | 66 (2) | 41 (2) | 201 (1) | 98 (1) | | | | |
| Elena | 130 (8) | 55 (8) | 204 (9) | 128 (9) | 388 (7) | 274 (7) | 532 (5) | 300 (5) |
| Average | 84 (49) | 42 (49) | 129 (43) | 110 (43) | 208 (43) | 206 (43) | 273 (40) | 291 (40) |

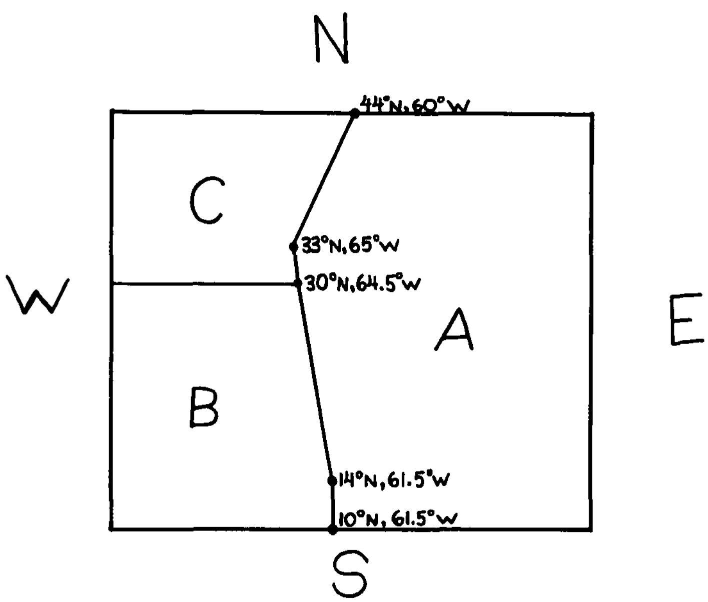



FIGURE 15.—Division of North Atlantic area (A, B, C) used in stratifying forecast statistics in table 18.

cases. Average errors indicate the NPGS optimal scheme excelled NHC-64 for 12 and 24 hr. while the latter surpassed the former at 48 hr., although even here two out of three storms representing 50 percent of the forecasts favor the NPGS scheme. From Miami, 72-hr. forecasts were not available, and 36-hr. statistics yield inconclusive results. For Carol, whose forecast times exactly matched those of NHC-64, the results show the NPGS scheme to be an improvement over NHC-64 at all forecast intervals.

## 7. STRATIFICATION OF ERROR STATISTICS BY AREA, TRACK, AND STORM STAGE

Atlantic: The Atlantic area was divided into three zones, A, B, and C, in accordance with a similar division used by the NHC group at Miami [7]. See figure 15. Area A represents the Atlantic area generally east of 60°W.; B covers the Caribbean, Gulf of Mexico, and Atlantic areas south of 30°N. and north and west of 60°W.; and C encompasses the eastern United States and ocean areas immediately to the east which are north of 30°N.

Table 18 shows the predominance of cyclone positions in areas A and B and the superiority of optimal NPGS forecast accuracy in the latter compared to A and C for all forecast time intervals. In the case of 72-hr. forecasts, errors in areas A and C, collectively, average about 100 percent greater than those in area B. Such statistics compare well with findings by Tracy [7] using the NHC–64 technique.

The distribution of forecast errors relative to path is also quite interesting. Without exception, forecast errors are less for all forecast intervals for cyclone stages before the time of recurvature. After-recurvature areas for the storm/hurricane stages are most frequently in C and northern sections of A as shown in [10].

The interrelationship of area and path are also manifest in the error statistics relative to cyclone stage. Table 18 indicates that, collectively, the intensifying tropical depression (TD dev) and tropical storm (*TS*) are associated with the most reliable results when using the optimal NPGS scheme. These stages are generally before recurvature and in area B or southwestern A. Hurricane (H) statistics are next best, partly due to inclusion of some after-recurvature cases in areas A and C. The extratropical (EXT) and dissipating tropical depression TD (dis) stages, which should be combined as case histories in [10], lead to the conclusion that the differences between the two stages are quite tenuous. All in all EXT and TD (dis) categories perform poorest and represent after-recurvature cases in area A for the most part.

Pacific: Table 19 for Pacific typhoons shows the breakdown by path only. Area analysis has not received the same focus as in the Atlantic and analysis by stage from published 1965 storm data [8] does not discriminate sufficiently between cyclone categories to warrant analysis like that presented for the Atlantic. Before recurvature, error values are much less than the overall average official errors while after recurvature the optimal NPGS errors jump by as much as 100 percent. These results closely parallel the Atlantic.

## 8. CONCLUSIONS

The NPGS scheme for forecasting tracks of tropical storms, hurricanes, and typhoons is objective, numerical, easy to apply, and readily adaptable to field use. The errors for forecast intervals up to 72 hr. are consistently below those from most other well-known subjective and objective techniques.

Part of the success of the NPGS scheme in relation to the official and NHC–64 forecasts may be ascribed to the following:

a) The best track vice operational track positions were used as initial cyclone locations from which NPGS

TABLE 18.—*1965 Atlantic hurricanes: error distribution for optimal NPGS SR 700 scheme by area, path and storm stage. Errors in nautical miles. Number of forecasts in parentheses*

| | Area | | | Recurvature | | Storm stage | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | Before | After | TD(dev) | TS | H | EXT | TD(dis) |
| $F^{12}_{12}$ | 50 (48) | 42 (34) | 46 (5) | 39 (63) | 67 (24) | 47 (15) | 36 (14) | 44 (50) | 74 (6) | 101 (2) |
| $F^{12}_{24}$ | 131 (45) | 97 (33) | 130 (5) | 95 (58) | 169 (25) | 72 (11) | 108 (13) | 116 (51) | 197 (6) | 220 (2) |
| $F^{12}_{36}$ | 235 (42) | 171 (31) | 256 (5) | 174 (54) | 294 (24) | 112 (8) | 209 (11) | 216 (52) | 328 (6) | 55 (1) |
| $F^{12}_{48}$ | 356 (41) | 269 (29) | 429 (5) | 276 (50) | 430 (25) | 219 (6) | 278 (9) | 327 (51) | 493 (6) | 351 (3) |
| $F_{72}$ | 628 (38) | 323 (27) | 675 (5) | 427 (46) | 680 (24) | 473 (4) | 404 (7) | 480 (50) | 869 (6) | 679 (3) |

TABLE 19.—*1965 Pacific typhoons: error distribution for optimal NPGS SR 500 scheme by path errors in nautical miles. Number of forecasts in parentheses*

| | Recurvature | |
|---|---|---|
| | Before | After |
| $F^{12}_{12}$ | 46 (70) | 79 (22) |
| $F^{24}_{24}$ | 84 (51) | 170 (21) |
| $F^{24}_{36}$ | 138 (45) | 251 (18) |
| $F^{12,24}_{48}$ | 189 (37) | 356 (20) |
| $F^{12,24}_{72}$ | 291 (24) | 499 (18) |

forecasts were generated, while the operational positions are germane to the official and NHC–64 statistics. However, all three techniques used the best track data for verifications. Thirteen mi. is the average difference between aircraft reconnaissance and the best track locations in the Pacific in 1965 [8]. Such a difference represents a range from about 25 percent to 4 percent of the magnitudes of the forecast errors for periods from 12 to 72 hr., respectively. This factor does not appear to change the conclusions cited to this point.

b) Perhaps more serious than a) above is the following. In the case of JTWC/FWC Guam the operational positions at forecast times (0600 and 1800 GMT) are determined by 3- to 12-hr. forecasts from fixes determined by recent land radar and/or aircraft reconnaissance observations or by surface/upper air analyses. Such a procedure puts the official forecast at a disadvantage compared to the research program used here. The magnitude of the disadvantage is difficult to assess.

c) As noted in section 3, *SR* analyses, 6 hr. after initial time, were used to forecast cyclone tracks out to 72 hr. This is not operationally realistic and may have contributed somewhat to the success of the NPGS scheme, particularly in the short-period forecasts as 12 and 24 hr.

Balancing the scale in favor of the relative merits of the NPGS scheme is the recent operational experience of JTWC/FWC Guam. In the summer of 1967 FNWF began an experimental numerical tropical cyclone steering program which utilizes the *SR* fields in essentially the same way as the research program outlined here. The movement forecasts are produced separately from *SR* analyses and prognostic fields. Guam has used these numerical-steering forecasts along with corrections for bias in the manner just described. Preliminary indications suggest that the accuracy of 24-hr. forecasts, accomplished under operational real time conditions, is commensurate with that shown in this paper, as performed under a post-season research environment.[3] Definite statements on this matter await extensive post-season analysis.

## 9. FINAL REMARKS AND AVENUES FOR FURTHER RESEARCH

The merits of the bias correction are derived from the information content inherent in the recent behavior of the storm relative to the numerical scheme used to predict it. This is a simple, however, unique, application of continuity. As such, the correction for bias using *SR* analyses only may be viewed as serving one or more of the following purposes. It compensates for a) the use of an improper steering field and/or derived current, and/or b) the use of an inappropriate level or layer in the *SR* steering field and/or c) erroneous information in the particular *SR* field selected as the steering medium, and/or d) changes with time in the *SR* steering field. The last point is tantamount to stating that the correction for bias, especially at increasing forecast intervals, substitutes for movement and development in the *SR* steering current, but, of course, with lag. Since prognostic fields are imperfect, especially in the Tropics, the procedure of using a bias correction to approximate changes in the *SR* field may be preferable. Experiments are being conducted at both the FNWF and the NPGS to determine the merits and deficiencies of using *SR* analyses only or *SR* analyses and prognoses in combination, to generate forecasts of tropical cyclone movement. Perhaps the temporal deterioration of the information content in the initial *SR* analyses suggests using a relatively reliable short period *SR* prognostic field, as the 36-hr., for cyclone forecasts from 36 to 72 hr.

More directly, a consistent bias in the numerical-steering program strongly suggests tuning the steering field or its derived current to the movement of tropical cyclones. In other words, changes may be made to the mathematical smoothing program to allow increased

[3] Private communication with personnel at JTWC/FWC Guam. See also [2].

meridional steering components as well as magnification of the basic zonal current.

Further, utilizing the geostrophic *SR* wind at the point of the storm center instead of a mean geostrophic wind from the area surrounding the storm is likely to give some increase in the steering values. Such a modification is already a part of the present FNWF experimental tropical cyclone steering program.

The possible modifications of the numerical forecast procedure according to storm stage, path, area, latitude, season, etc. are almost limitless. Given what appears to be a suitable numerical-steering environment, namely *SR*, various statistically adjustments may now be derived to reduce the errors, especially after recurvature, during the dissipating stage and in east ocean areas.

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## CORRECTION NOTICE

Vol. 96, No. 3, p. 142, 1st line after equation (12): $S^2_\Delta(R)$ should read $\sigma^2_\Delta$ $(R)$; p. 143, figure 3 caption should include—Curve 1: $|\Delta\epsilon| \leq 45$ m. Curve 2: $|\Delta\epsilon| > 45$ m. Curve 3: value assigned to first-guess field; p. 145, equation (29): a left parenthesis should precede $\epsilon^*_{l,m-1}$.